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Are renewable energy policies climate friendly? The role of capacity constraints and market power☆

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ABSTRACT

This paper studies the impacts of renewable energy support policies on energy prices, fossil fuel supply and thus carbon emissions from fossil fuels. Such supports are climate friendly if the renewables are already competitive against fossil fuels. But if the renewables are not yet competitive, the climate change impacts are often ambiguous and are sensitive to capacity constraints of renewables production and to the fossil fuel market structure. If the renewables do not have capacity constraints, then the subsidies are subject to the Green Paradox under perfect competition, but might be climate friendly under monopoly. Supports for capacity constrained renewables under perfect competition lead to more current fossil fuel supply but delay fossil fuel exhaustion time, and these effects are reversed under monopoly. Our results highlight the importance of considering the long-term effects on fossil fuel supply as well as capacity constraints and market power in designing renewable energy policies and evaluating their carbon footprints.

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1. Introduction

To combat global climate change and to promote energy security and employment, major economies throughout the world are promoting the development of renewable energies such as wind, solar, and biofuels. The climate change argument is rather simple: clean renewable energies will substitute for fossil fuels, thereby reducing greenhouse gas (GHG) emissions and alleviating the threat of climate change. However, renewable energy policies are not without controversies, especially when indirect market effects are taken into consideration. For instance, Graff Zivin et al. (2014) show that the environmental impact of solar energy in the US depends critically on the location of coal based power plants that are replaced by solar energy. In the case of corn based ethanol in the US, Searchinger et al. (2008) and Hertel et al. (2010) argue that additional carbon emissions due to indirect land use effects can dominate any carbon savings from ethanol replacing gasoline: corn ethanol leads to higher food

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prices, which in turn will cause more land, including forest land, to be converted into agriculture in developing nations, releasing large amounts of carbon. In fact, much of the debate surrounding ethanol has centered on price changes in the feedstock markets (corn and other commodities) and their effects on food security and land uses. Recently studies on indirect market effects have been extended to include the liquid fuel market, and static international trade models are used to evaluate the impacts of US domestic ethanol policies on domestic and international gasoline prices and consumption levels (Rajagopal et al., 2011; de Gorter and Drabik, 2011; Thompson et al., 2011; Grafton et al., 2014; and Allaire and Brown, 2015). Due to the small share of biofuels in the liquid fuel market, these studies typically find rather limited impacts of biofuel policies on gasoline consumption and GHG emissions. Holland et al. (2009) further show, in a static model, that even when biofuels do have a lower carbon footprint, a policy such as a low carbon fuel standard that limits carbon intensity of fuels does not necessarily reduce overall carbon emissions.

In this paper, we evaluate the effects of renewable energy policies in the energy market in a *dynamic* model so as to evaluate the *long-term* economic and GHG impacts of renewable energy policies. We show that these effects depend critically on two important factors: the market structure of the fossil fuel sector and the presence of capacity constraints in producing renewable energies. We consider two polar cases of market structure, namely perfect competition and monopoly. Renewable energies are supplied competitively and modeled as perfect substitutes for fossil fuels. We find that the effects of renewable policies can go in opposite directions depending on the nature of the market structure and the presence or absence of limited production capacity constraints. For instance, subsidies to pure backstops without capacity constraints in a competitive market raise the supply of fossil fuels and thus GHG emissions in early periods. In contrast, the same subsidies reduce the early period supply of fossil fuels in a monopolistic fossil fuel market, and if the renewable energy faces capacity constraints, its subsidies delay the exhaustion of fossil fuels even in competitive markets.

There is a large literature on the market structure of fossil fuels (see, for example, Smith, 2009 and Huppmann and Holz, 2012 for oil, Gabriel et al., 2012 for natural gas, Graham et al., 1999 and Truby, 2012 for coking coal, and Trüby and Paulus, 2012 for steam coal). Some of the markets tend to be competitive while significant market power exists in others. For example, while coal and gas markets tend to be competitive, OPEC has been a major cartel in the international oil market for decades. National oil companies, which account for over 55% of world production in 2010, are often given monopoly power in their domestic oil markets, as in the case of Russia, China and Venezuela (USEIA, 2012). By focusing on the polar cases of perfect competition and monopoly, we highlight in a tractable model the importance of market structures in determining the long-term consequences of renewable policies.

While traditionally renewables have been modeled as pure backstops, i.e., resources with constant marginal costs that supply the entire market once they become competitive,[1] many renewable energies are limited in their production capacities.[2] For example, the capacity of biofuels is limited by land availability and competing demands for food and feed. Holland et al. (2015) shows that for both first and second generation biofuels, the marginal cost tends to be flat until the output reaches a certain threshold value and then shoots up significantly. The threshold acts as a type of "capacity constraint," limiting the degree to which biofuels can replace fossil fuels. Capacity constraints could limit wind and hydroelectric power as well because as prime wind and hydro sites are used up and less favorable sites are utilized, the siting cost will increase significantly. Less favorable sites also tend to be located far away from consumption centers, leading to significant transmission costs. Capacity constraints can also be imposed by government policies. For instance, starting in 2006, China strengthened its entry regulation on corn and wheat based ethanol production plants out of concerns about food security, effectively putting a cap on how much first generation biofuel can be produced within the country (Chang et al., 2012). Restrictions on nuclear power plants and hydroelectric dams, out of safety and ecosystem related concerns, are also examples of policy induced capacity constraints.

Capacity constraints provide an additional dimension of renewable energy development that has not been captured by previous studies, namely technology innovation or government policies that relax the capacity constraints. As we show in this paper, expanding a renewable energy's capacity can lead to qualitatively different impacts on fossil fuel supply from reducing its marginal costs. Explicitly modelling capacity constraints of renewable energies can also generate dynamic patterns of fossil fuel extraction and energy prices that are "unusual" but relevant. Wang and Zhao (2013) show that in a monopolistic fossil fuel market, as a capacity-constrained renewable substitute becomes competitive, the monopolist will flood the market to keep the fossil fuel price at the renewable's marginal cost so as to stave off the renewable supply, before eventually letting the renewable into the market, causing the fossil fuel price to jump up.[3] The price jumps can be discussed only when the renewable substitute is capacity constrained.

Our paper is related to and extends the Green Paradox literature pioneered by Sinn (2008), which argues that government policies that help reduce the demand for fossil fuels could raise the supply of fossil fuels in the near future and speed up their exhaustion, thereby exacerbating the threat of climate change. For example, increasing the tax rate on carbon could depress the prices of fossil fuels more in the future than at present, encouraging fossil fuel owners to increase current extraction. Moving fossil fuel supplies from the future to present is undesirable since CO_2 is close to being a stock pollutant. The Green Paradox framework has been adopted to study a variety of renewable energy policies in dynamic settings (see Sinn (2012) for a sum-

[1] See, for example, Hoel (1978, 1983, 2008), Dasgupta and Stiglitz (1981), Dasgupta et al. (1982, 1983) and Chakravorty et al. (2006, 2008).

[2] Amigues at al (1998) and Holland (2003) are the few papers in the literature that show the important role of capacity constraints of renewable resources, focusing on how capacity constraints could change the order of extraction of heterogeneous resources due to the scarcity rent generated by the capacity constraints.

[3] This type of "stave-off" behavior is similar to OPEC's response to the US shale revolution since 2014.

mary and van der Werf and Di Maria (2012) for a nice review of the literature). However, in most applications one has to depart from the notion of "strong Green Paradox," which is based on the net present value of future stream of environmental damages, since it is difficult to form accurate forecasts of fossil fuel supplies in all future periods (Gerlagh, 2011). Instead, researchers have resorted to the concept of "weak Green Paradox" and addressed qualitatively whether a policy can increase climate damage through certain characterizable channels. Different channels have been used in the literature. Some papers focus on the exhaustion date or accumulated extraction of fossil fuels (van der Ploeg and Withagen (2012); Grafton et al. (2012)), while others emphasize the current extraction level (Sinn, 2008; Gerlagh, 2011; van der Werf and Di Maria, 2012). Under typical modeling approaches that treat renewables as perfect backstops in competitive markets, the two notions are consistent with each other: if a policy (e.g., price subsidy for the backstop) increases current extraction of fossil fuels, it also speeds up their exhaustion. However, we show that the two effects tend to be opposite to each other once capacity constraints and imperfect competition are accounted for. One might argue that early period extraction should be more important than the exhaustion date of fossil fuels since the discount rate is positive and fossil fuels will not be exhausted in the near future (e.g., within one century). However, if the cost of renewable energies is reduced to sufficiently low levels at sufficiently fast rates, fossil fuels might be "economically exhausted" relatively soon. In this paper, we take into consideration both effects and define weak Green Paradox as satisfying both conditions of raising early period extraction and speeding up the exhaustion date of fossil fuels.

Within the Green Paradox literature, our paper is closely related to Gerlagh (2011), van der Ploeg and Withagen (2012), and Grafton et al. (2012). Gerlagh (2011) considers three stylized models of fossil fuel extraction facing competition from renewable energies - (i) a benchmark model with constant extraction cost of fossil fuels and a perfect backstop (one with a constant marginal cost and unlimited supply), (ii) a model with a stock dependent fossil fuel extraction cost and a perfect backstop, and (iii) a model with a constant extraction cost of fossil fuels and an imperfect backstop that faces increasing marginal costs. For model (i), he shows that reducing the cost of the backstop resource raises both current emissions and the net present value of climate damages from fossil fuels, thereby generating a Green Paradox. However, when the energy inverse demand function is linear, the Green Paradox may not arise in models (ii) or (iii).[4] van der Ploeg and Withagen (2012) adopts a model similar to Gerlagh's model (ii) to investigate the timing of switching to the backstop renewable energy and the amount of fossil fuels remaining unexploited. They show that subsidizing the backstop renewable has two opposing effects: speeding up fossil fuel extraction and leaving more fossil fuels never unexploited. The net impact depends on the relative magnitude of the two effects. They characterize the conditions under which the Green Paradox may arise in different scenarios, including a competitive fossil fuel market, monopolistic supply of fossil fuels and imperfect backstop with an increasing marginal cost. Grafton et al. (2012) extends model (iii) of Gerlagh (2011) and shows that subsidies for renewable energies can reduce fossil fuel demand through direct substitution, but also might increase fossil fuel demand due to depressed energy prices. The net impact on the date of exhaustion of fossil fuels depends on the demand elasticity for energy and supply elasticity for renewable energies. Both Grafton et al. (2012) and van der Ploeg and Withagen (2012) assume convex production costs of renewables to allow simultaneous use of fossil fuels and renewables. To obtain analytical solutions, they focus on isoelastic and quadratic cost functions.

We depart from these papers by focusing on comparing the impacts of renewable policies across different combinations of market structures and capacity constraints. We make a number of simplifying assumptions, including constant and stock independent production costs of fossil fuels and constant production costs of renewables (subject to capacity constraints). Technically, we take the rather "standard" approach of Hartwick (1978), which has been widely utilized in the literature (e.g., Holland (2003) for competitive markets, and Hoel (1978) and Groot et al. (2003) for imperfect competition). Our major contribution is to show that the effects of renewable energy policies are highly dependent on the fossil fuel market structure and the existence of capacity constraints in producing renewables. Further, by explicitly modeling capacity constraints, we are able to distinguish between different types of renewable energies by their costs as well as capacity limits, and study policies observed in the real world that target production capacities. Moreover, some of the conclusions found in the Green Paradox literature will be reversed once capacity constraints are taken into account. For example, in a similar setting but without capacity constraints, Grafton et al. (2012) shows that the effect of renewable price subsidies on the exhaustion time of fossil fuels is independent of the fossil fuel market structure. In our model, by contrast, the effects are highly sensitive to whether the fossil fuel market is competitive or not.

The rest of the paper is organized as follows. In Section 2 we set up the model and study the policy impacts in a perfectly competitive fossil fuel market. We analyze the monopolistic fossil fuel market in Section 3. We discuss the role of capacity constraints and market power in Section 4 and conclude in Section 5. Appendix A provides additional technical details and Appendix B contains proofs of the propositions.

2. A competitive fossil fuel market

We study a partial equilibrium model where energy production costs and government policies are exogenously given. We consider four energy products, including fossil fuels, a capacity constrained renewable energy that is already competitive (denoted as R1), a capacity constrained renewable that is not competitive yet (denoted as R2), and a pure backstop that has

[4] Hoel (2008) considers a model similar to model (i) of Gerlagh (2011). He shows that when different countries implement different carbox taxes, reducing the cost of backstop induces more countries to use the backstop but also depresses the energy price, thereby encouraging fossil fuel use. Whether Green Paradox arises depends on which of the two effects is dominant.

no capacity constraint and is not competitive yet. To fix ideas, R1 could be sugarcane based biofuel that is competitive even when gasoline prices are low, and R2 could be second generation biofuels that are not competitive yet. Nuclear fusion or solar has been considered as the ultimate backstop if one goes beyond the photovoltaic technology (e.g., solar energy could be used to produce hydrogen gas). We assume that the four energies are perfect substitutes and the supplies of renewable energies are perfectly competitive. [5] In this section, we assume that the fossil fuel sector is also perfectly competitive - we study the case of monopolistic fossil fuel markets in the next section.

Let $q_F(t)$ and $X(t)$ be the supply and remaining reserve of fossil fuels at t with starting reserve X_0. Let $q_{R1}(t)$ and $q_{R2}(t)$ be the supply of R1 and R2 in period t and $\overline{q}_{R1}$ and $\overline{q}_{R2}$ be their (per period) production capacity limits, arising from resource constraints or from government policies. Thus $q_{R1}(t) \le \overline{q}_{R1}$ and $q_{R2}(t) \le \overline{q}_{R2}$ for all t. Let $q_R(t) = q_{R1}(t) + q_{R2}(t)$ and $\overline{q}_R = \overline{q}_{R1} + \overline{q}_{R2}$ denote the total supply and total capacity of R1 and R2. Finally, let $q_B(t)$ be the supply of the backstop energy in period t. For simplicity, we assume that all energy products have constant marginal production costs and no fixed costs. Let the unit production costs of the four energies be c_F, c_{R1}, c_{R2} and c_B, with $c_F < c_{R1} < c_{R2} < c_B$. We study the effects of government policies that reduce these costs and/or increase $\overline{q}_{R1}$ and $\overline{q}_{R2}$.

Let the stable inverse demand function for energy be $p(t) = h(Q(t))\ \forall t$ with $h'(Q) \le 0$ where $p(t)$ denotes the energy price in period t and $Q(t) = q_F(t) + q_R(t) + q_B(t)$ is the total energy consumption. We assume

$$\overline{q}_R < h^{-1}\left(c_B\right), \tag{1}$$

where $h^{-1}(\cdot)$ is the energy demand function. That is, the capacity constraint is sufficiently limiting so that even when R1 and R2 are supplied at their full capacity, they alone cannot drive the backstop out of the market. Similarly, they cannot drive fossil fuels out of the market either:

$$\overline{q}_{R1} < h^{-1}(c_{R1}) \quad \text{and} \quad \overline{q}_R < h^{-1}(c_{R2}). \tag{2}$$

Finally, we assume $c_{R1} < p(0) < c_{R2}$ so that at present R1 is competitive against fossil fuels (i.e., it is supplied at full capacity) but R2 is not. The condition depends on the initial stock X_0 as well as production costs, and in Appendix A, we spell out the required range of X_0 for this condition to hold.

2.1. Energy market equilibrium

Since renewables producers are price takers with constant marginal production costs, the optimal supplies of capacity constrained renewables are given by

$$q_{Ri}(t)\begin{cases} = 0, & \text{if } p(t) < c_{Ri} \\ \in \left[0, \overline{q}_{Ri}\right], & \text{if } p(t) = c_{Ri} \\ = \overline{q}_{Ri}, & \text{if } p(t) > c_{Ri} \end{cases}, \quad i = \{1, 2\}, \tag{3}$$

and the optimal supply of the pure backstop is

$$q_B(t)\begin{cases} = 0, & \text{if } p(t) < c_B \\ \ge 0, & \text{if } p(t) = c_B \end{cases}. \tag{4}$$

Since the backstop has unlimited supply, energy price $p(t)$ can never exceed c_B.

When the fossil fuel sector is competitive, the (representative) fossil fuel producer takes the market price trajectory $\{p(t), t \ge 0\}$ as given and chooses its extraction path according to

$$\max_{\{q_F(t)\},\Gamma} \int_0^{\Gamma} e^{-rt}\left[p(t)\, q_F(t) - c_F q_F(t)\right] dt$$

$$\text{s.t.} \quad \dot{X}(t) = -q_F(t); \quad \int_0^{\Gamma} q_F(t)\, dt = X_0;$$

where r is the market interest rate, Γ is the ending time when the fossil fuel is driven completely out of the market, $X(t)$ is the remaining stock at time t, and X_0 is the initial stock level. Since the extraction cost is stock independent, stock X_0 will be exhausted. Forming the Hamiltonian and optimizing, we have the firm's optimal supply given by

$$q_F(t)\begin{cases} = 0 & \text{if } p(t) < c_F + \lambda e^{rt} \\ \ge 0 & \text{if } p(t) = c_F + \lambda e^{rt} \end{cases} \tag{5}$$

[5] The main end uses of these energies are electricity and transportation. The substitution of different energy products requires adjusting the energy contents and conversion to different end uses. For example, oil can be converted to transportation use through gasoline and diesel, and solar can be converted to electricity through photovoltaic technology and then used for transportation through electric cars. Chakravorty et al. (1997) describes such conversions in detail and computes the conversion cost for different energy products and different end uses.

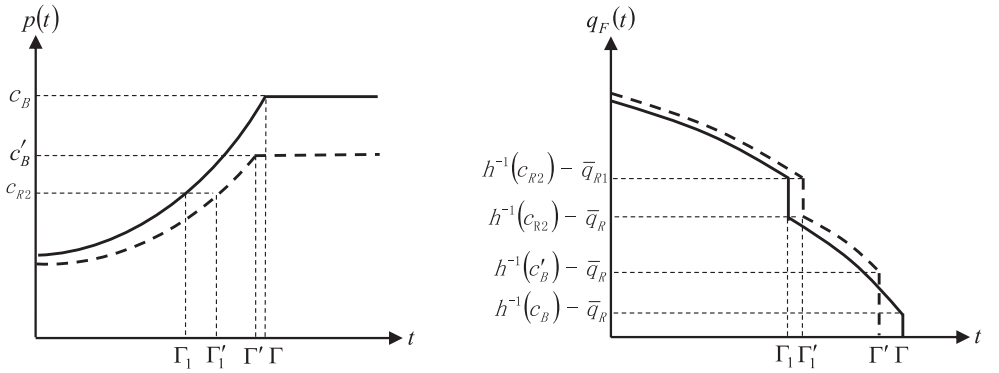


Fig. 1. Impacts of backstop price subsidies: perfect competition.

where λ is the present value Hotelling rent (or in-situ value). The term $c_F + \lambda e^{rt}$, called the augmented marginal cost (AMC) by Holland (2003), measures the "total" marginal cost that includes the scarcity value of fossil fuels in the ground. The firm's extraction decision is made by comparing this cost with the energy price.

The competitive equilibrium is characterized by the supply functions (3), (4), and (5), and the market clearing condition $h\left(q_F(t)+q_R(t)+q_B(t)\right)=p(t)$, $\forall t$. From (5), we know $p(t)=c_F+\lambda e^{rt}$ if $q_F(t)>0$: as long as the fossil fuels are supplied, the AMC completely determines the energy price. From the beginning, energy price increases over time and gradually crosses the costs of various renewable energies, at which points these energies start to be supplied at full capacities. Let Γ_1 be the time when the energy price reaches the cost of R2, i.e., $c_{R2}=c_F+\lambda e^{r\Gamma_1}$. We can then divide the equilibrium path into several stages. During the first stage $t\in\left[0,\Gamma_1\right)$, $p(t)<c_{R2}$: R2 is not competitive but R1 is supplied at its full capacity. The fossil fuels meet the residual demand:

$$q_F(t)=h^{-1}\left(c_F+\lambda e^{rt}\right)-\overline{q}_{R1},\quad t\in[0,\Gamma_1). \tag{6}$$

During the second stage $t\in\left[\Gamma_1,\Gamma\right)$, $c_{R2}\le p(t)<c_B$ with $p(\Gamma)=c_B$: both types of capacity constrained renewable are competitive and supplied at their full capacities, but the backstop is still not competitive. The supply of fossil fuels is given by

$$q_F(t)=h^{-1}\left(\lambda e^{rt}+c_F\right)-\overline{q}_R,\quad t\in[\Gamma_1,\Gamma). \tag{7}$$

Since the backstop has no capacity constraints, fossil fuels are exhausted at time Γ, at which point the backstop becomes competitive and supplies the market together with capacity constrained renewables. For $t\ge\Gamma$, $p(t)=c_B$, $q_F(t)=0$, $q_{Ri}(t)=\overline{q}_{Ri}$, $i=\{1,2\}$, and the backstop supplies the residual demand: $q_B(t)=h^{-1}\left(c_B\right)-\overline{q}_R$.

Fig. 1 illustrates the price and supply paths of fossil fuels (solid curves). The paths are characterized by three variables, $\left\{\lambda,\Gamma_1,\Gamma\right\}$, which are determined by

$$\int_0^{\Gamma}h^{-1}\left(c_F+\lambda e^{rt}\right)dt-\Gamma\overline{q}_{R1}-\left(\Gamma-\Gamma_1\right)\overline{q}_{R2}=X_0, \tag{8}$$

$$c_F+\lambda e^{r\Gamma_1}=c_{R2}, \tag{9}$$

$$c_F+\lambda e^{r\Gamma}=c_B. \tag{10}$$

2.2. Impacts of renewable energy policies

Through comparative analysis of (8)–(10), we can evaluate the impacts of renewable energy policies on fossil fuel supply and the associated GHG emissions. We first define the *climate friendliness* and *(weak) Green Paradox* of renewable policies.

Definition. *A renewable energy policy is* climate friendly *if it reduces the extraction of fossil fuels in early periods and postpones the fossil fuels' exhaustion time.*

A renewable energy policy is subject to the (weak) Green Paradox *if it raises fossil fuel extraction in early periods and speeds up the exhaustion time of fossil fuels.*

This definition extends the Green Paradox literature that has focused on either fossil fuel supply in early periods or the exhaustion date of fossil fuels, and as we show later, is needed since the two criteria are not always consistent with each other once capacity constraints and imperfect competition are taken into consideration. Further, since the entire stock of fossil fuels X_0 will be extracted, all of the carbon stored in fossil fuels will eventually be emitted to the atmosphere, leading to a fixed amount

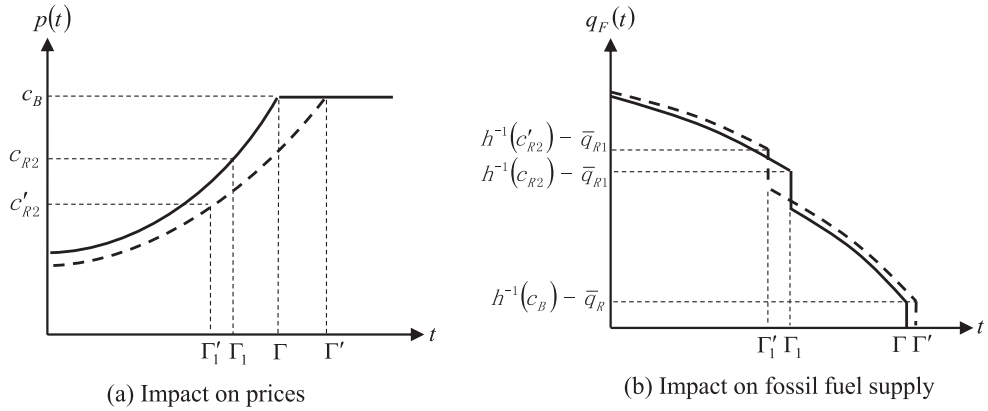


Fig. 2. Impacts of R2 price subsidies:perfect competition.

of total CO_2 emissions over all future years.[6] The climate benefits of renewable policies, therefore, arise only from delaying carbon emissions. Delaying emissions is beneficial both because future climate damages are discounted, and because CO_2 is a stock pollutant with a low rate of dissipation, so that carbon released in early periods accumulate in the atmosphere, leading to damages both now and in the future. Hoel (2009) derives a sufficient condition under which delaying current GHG emissions to the future would be beneficial and uses numerical examples to illustrate that the condition is likely to hold.

In what follows, we define price subsidies as policies that reduce the costs or raise the prices of renewable energies (e.g., favorable feed-in tariffs), and capacity expansion policies as those that raise the production capacity of renewables $\overline{q}_{R1}$ and $\overline{q}_{R2}$. Some policies affect both the prices and capacities of renewables. For example, an R&D subsidy that supports renewable energy innovations can reduce the costs as well as expand the capacities of renewable energies. In the next proposition, we study the two kinds of policies separately, and evaluate their effects on energy prices, fossil fuel supplies, and two critical times including Γ_1, the moment when R2 becomes competitive, and Γ, the moment when fossil fuels are exhausted.

Proposition 1. *Suppose the energy market is perfectly competitive. Then*

(1) $\partial\lambda/\partial c_B > 0$; $\partial\Gamma_1/\partial c_B < 0$; $\partial q_F(t)/\partial c_B < 0$ *for* $t \le \Gamma$; *and* $\partial\Gamma/\partial c_B > 0$: *backstop price subsidies reduce the value of fossil fuels and thus the energy price, and delay the arrival time of R2. They raise the extraction and speed up the exhaustion of fossil fuels, leading to Green Paradox.*

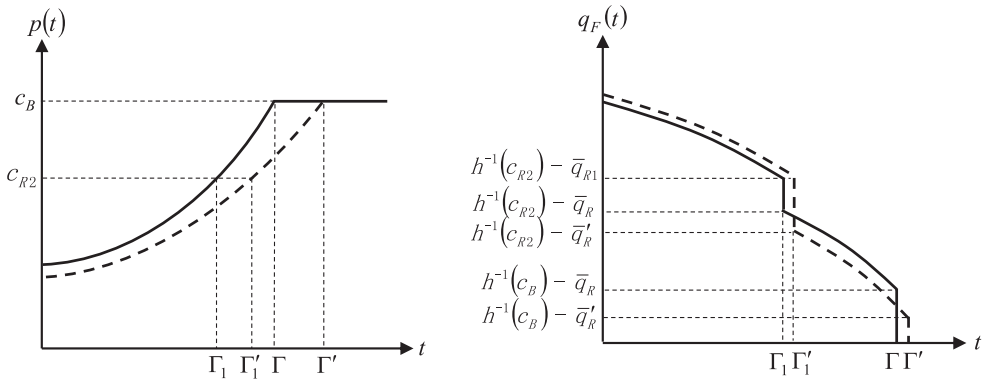
(2) $\partial\lambda/\partial c_{R2} > 0$; $\partial\Gamma_1/\partial c_{R2} > 0$; $\partial q_F(t)/\partial c_{R2} < 0$ *for* $t \le \Gamma_1$; *and* $\partial\Gamma/\partial c_{R2} < 0$: *R2 price subsidies reduce the value of fossil fuels and thus the energy price, and speed up the arrival time of R2. They raise the early period extraction but delay the exhaustion of fossil fuels, leading to ambiguous climate change effects.*

(3) $\partial\lambda/\partial\overline{q}_{R2} < 0$; $\partial\Gamma_1/\partial\overline{q}_{R2} > 0$; $\partial q_F(t)/\partial\overline{q}_{R2} > 0$ *for* $t < \Gamma_1$; *and* $\partial\Gamma/\partial\overline{q}_{R2} > 0$: *capacity expansion policies for R2 reduce the value of fossil fuels and thus the energy price, and delay the arrival time of R2. They raise the early period extraction but delay the exhaustion time of fossil fuels, leading to ambiguous climate change effects.*

(4) $\partial\lambda/\partial\overline{q}_{R1} < 0$; $\partial\Gamma_1/\partial\overline{q}_{R1} > 0$; $\partial\Gamma/\partial\overline{q}_{R1} > 0$; *and if* $h(\cdot)$ *is (weakly) convex,* $\partial q_F(t)/\partial\overline{q}_{R1} < 0$ *for small* t: *capacity expansion policies for R1 reduce the value of fossil fuels and thus the energy price, and delay the arrival time of R2 as well as the exhaustion time of fossil fuels. If the energy demand function is weakly convex (e.g., linear), they also reduce the early period extraction of fossil fuels, leading to climate friendly effects.*

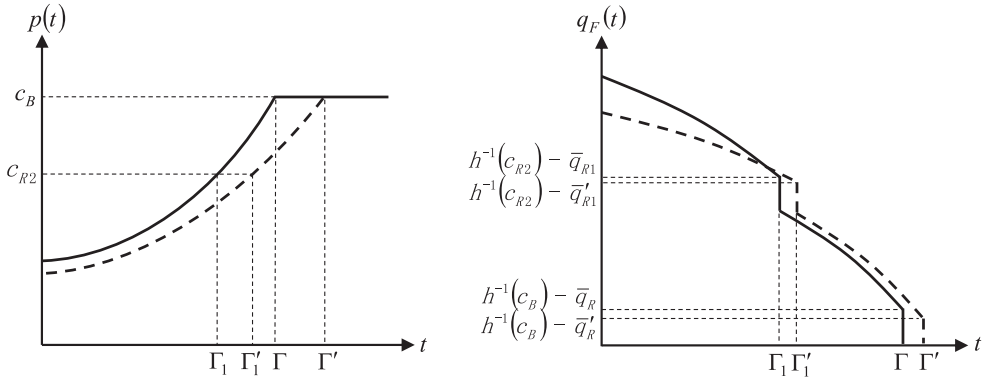
The Proof is in Appendix B, and Figs. 1–4 illustrate the effects of the renewable policies on fossil fuel price and extraction paths. Since renewable energies and fossil fuels are substitutes, policies that reduce the costs or expand the capacities of renewables will render the fossil fuels less competitive and thus reduce the Hotelling rent and the energy prices in all periods. These results are reflected in Panels (a) of all four Figures. However, energy price reductions, although raising total energy consumption, do not always lead to higher fossil fuel extraction since the increased demand might be met by increased supplies of R1 and/or R2. The exception occurs in Proposition 1(1) and Fig. 1, where the costs and capacities of R1 and R2 are fixed. Thus, backstop subsidies, by depressing the prices of fossil fuels, delays the time when R2 becomes competitive, thereby raising fossil fuel extraction and speeding up its exhaustion, leading to Green Paradox. In contract, in Proposition 1(2) and Fig. 2(b), the

[6] Total exhaustion of X_0 is due to our assumption that the extraction costs are stock independent. Otherwise, renewable policies could affect the ending stock of fossil fuels that are never extracted and thus the total amount of CO_2 that are emitted. Instead of explicitly modeling the ending stock, we let X_0 be the total amount of fossil fuels that will end up being extracted. This amount could be the stock that can be economically extracted over time. Alternatively, in the context of climate change, it can also be the maximum amount of fossil fuels that can be extracted in order to meet certain climate change goals, e.g., 2^oC above pre-industrial revolution levels, amounting to 2900 $GtCO_2$, 1900 Gt of which is already "extracted" during 1870–2011 (IPCC AR5). We thank an anonymous reviewer for making these observations.



(a) Impact on prices (b) Impact on fossil fuel supply

Fig. 3. Impacts of R2 capacity expansion policies: perfect competition.



(a) Impact on prices (b) Impact on fossil fuel supply

Fig. 4. Impacts of R1 capacity expansion policies: perfect competition.

reduction of c_{R2} pushes up fossil fuel supplies in earlier periods but also speeds up the arrival time of R2. There is thus a period $[\Gamma', \Gamma]$ in Fig. 2(b) during which fossil fuel supplies are reduced by the policy. In fact, the supply reduction dominates the supply increase in other periods so that fossil fuels are exhausted at a later time. In Fig. 3(b), an increase in capacity $\overline{q}_{R2}$ raises fossil fuel supplies in earlier periods and reduces the supplies in later periods. Again, the supply reduction dominates so that fossil fuels are exhausted at a later time. Thus price and quantity supports for R2 have ambiguous carbon impacts: they are not climate friendly, nor do they lead to Green Paradox.

Since R1 is already competitive (and thus supplied at its full capacity), further reduction of its cost c_{R1} does not have any impact on fossil fuel supplies. If its capacity $\overline{q}_{R1}$ expands, the exhaustion time of fossil fuels is delayed, but there are two opposing effects on the time pattern of fossil fuel supplies. On the one hand, q_F decreases given fixed total energy demand since R1 is a perfect substitute for fossil fuels. On the other hand, since the energy price decreases, the total energy demand rises. Further, since $\partial\lambda/\partial\overline{q}_{R1} < 0$, and the energy price is $p(t) = c_F + \lambda e^{rt}$, the energy price is reduced more in future periods. Thus, we expect that the energy price effect dominates in future periods, and the substitution effect dominates in earlier periods. This result, although intuitive, cannot be proved without specifying the functional form of energy demand. Proposition 1 (4) and Fig. 4 show that this is indeed the case when the demand function is weakly convex.

The results in Proposition 1 are summarized in the second and third columns of Table 1, where "+" and "-" signs represent climate friendly and unfriendly impacts respectively. Although the backstop and capacity constrained renewables are assumed to be perfect substitutes, they have different impacts on fossil fuel supplies due to the existence or absence of capacity constraints. To further appreciate the importance of capacity constraints, it is useful to compare our results to those of Grafton et al. (2012), which has a similar setting except that there are no capacity constraints and the renewable supply and energy demand functions are either both linear or both isoelastic. Although not explicitly stated, careful reading of Grafton et al. (2012) reveals that the impacts of a renewable subsidy on earlier extraction of the fossil fuel and on its exhaustion date are consistent with each other. Specifically, under the linear setting, the subsidy reduces early extraction and delays exhaustion, while under the isoelastic setting, the subsidy raises early extraction and speeds up exhaustion. Again, in Grafton et al. (2012), as in

Table 1
Summary of climate change impacts of renewable policies.

	Competitive Market		Monopolistic Market	
	Current production	Exhaustion time	Current production	Exhaustion time
c_B	−	−	+	−
c_{R2}	−	+	+	−
$\overline{q}_{R2}$	−	+	+	−
$\overline{q}_{R1}$	+	+	+	+

many other studies on the Green Paradox, there is no need to distinguish between the early extraction effect and the exhaustion date effect since the two effects are always consistent with each other. We have shown that the introduction of capacity constraints changes this result and makes it necessary to enrich the definition of (weak) Green Paradox by explicitly including both effects. Grafton et al. (2012) further shows that their conclusions in the linear setting carry over to the case of a monopolistic fossil fuel sector. However, as we show next, once the capacity constraints are accounted for, the impacts of renewable policies in a monopolistic market tend to be the opposite of those under perfect competition.

3. Monopolistic fossil fuel market

Fossil fuel markets are often characterized by imperfect competition (Loury, 1986; Polasky, 1992). In this section, we show that imperfect competition can significantly affect the climate change impacts of renewable energy policies. To sharpen our analysis, we focus on an extreme scenario where the fossil fuel sector is controlled by a monopolist while maintaining the assumption that the renewable energies are supplied by competitive firms. We adopt a cartel-fringe modeling framework and study equilibria in open loop strategies; such strategies are time consistent since the followers, i.e., the renewable energy firms, do not optimize dynamically. In other words, the monopolist does not have incentive to make time inconsistent promises about its future extraction paths in order to influence the current period decisions of the renewable firms as the latter only optimizes statically in the current period, in response to the monopolist's current period decisions.

3.1. Energy market equilibrium

The optimal supplies of renewable energies are still given by (3) and (4). The monopolist acts as the dominant firm in the energy market, and thus incorporates the responses of renewable energies in (3) and (4) in choosing its optimal extraction path:

$$V(\cdot) = \max_{\{q_F(t)\},T} \int_0^T e^{-rt} \left[h\left(q_F(t) + q_R(t) + q_B(t)\right) q_F(t) - c_F q_F(t) \right] dt \tag{11}$$

$$\text{s.t.} \quad \dot{X}(t) = -q_F(t); \ \int_0^T q_F(t)\, dt = X_0; \ (3); \ (4),$$

where T is the exhaustion time of the fossil fuel stock, and $V(\cdot) \equiv V\left(X_0, c_F, c_{R1}, c_{R2}, c_B, \overline{q}_{R1}, \overline{q}_{R2}\right)$ is the value function of the monopolist's maximization problem. We assume the revenue function $h\left(q_F + q_R + q_B\right) q_F$ is concave in q_F given q_R and q_B.

The current value Hamiltonian of (11) is

$$H(t) = h\left(q_F(t) + q_R(t) + q_B(t)\right) q_F(t) - c_F q_F(t) - \mu e^{rt} q_F(t) \tag{12}$$

where μ is the present value Hotelling rent. Free choice of exhaustion time T leads to the transversality condition

$$H(T) = h\left(q_F(T) + q_R(T) + q_B(T)\right) q_F(T) - c_F q_F(T) - \mu e^{rT} q_F(T) = 0. \tag{13}$$

Since the monopolist is the dominant firm, it takes into consideration the supply functions of the renewable energies (equations (3) and (4)) in making its optimal decisions. As is typically done in cartel-fringe models (Carlton and Perloff, 2004), the fringes' supply functions are used to form the residual demand curve and the associated marginal revenue curve facing the monopolist, shown in Fig. 5(a). Given the downward slopping energy demand function $h^{-1}(\cdot)$, represented by the dash-dot line in Fig. 5(a), the residual demand facing the monopolist, represented by the bold dotted lines, is obtained by subtracting from the total demand the supplies of renewables given in (3) and (4). When $p < c_{R2}$, only R1 is competitive and it is supplied at $\overline{q}_{R1}$. The residual demand (RD1) is obtained by subtracting $\overline{q}_{R1}$ from the total energy demand and is downward slopping. When $p = c_{R2}$, R2 firms are indifferent about supplying the market between zero and $\overline{q}_{R2}$, resulting in a flat residual demand (RD2). As R2 supplies at full capacity for $p > c_{R2}$, the residual demand curve is obtained by shifting the total demand curve to the left by the amount of $\overline{q}_{R1} + \overline{q}_{R2}$ (RD3). The residual demand becomes flat again at $p = c_B$ as the backstop becomes competitive and therefore caps the energy price (RD4).

Based on the residual demand curves, the monopolist's marginal revenue (MR) curves are represented by the solid lines in Fig. 5(a) and reproduced in Fig. 5 (b). For the downward slopping segments of the residual demand curve, i.e., RD1 and RD3, the MR curves (which equals $h + h' q_F$), labeled as Seg1 and Seg3 in Fig. 5(b), lies below the residual demand. The MR curves are

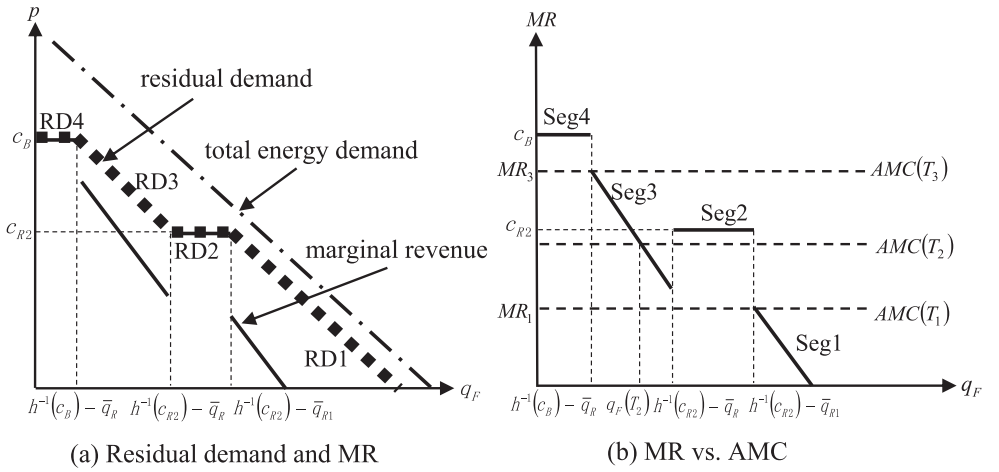


Fig. 5. The monopolist's optimal price and quantiy choices.

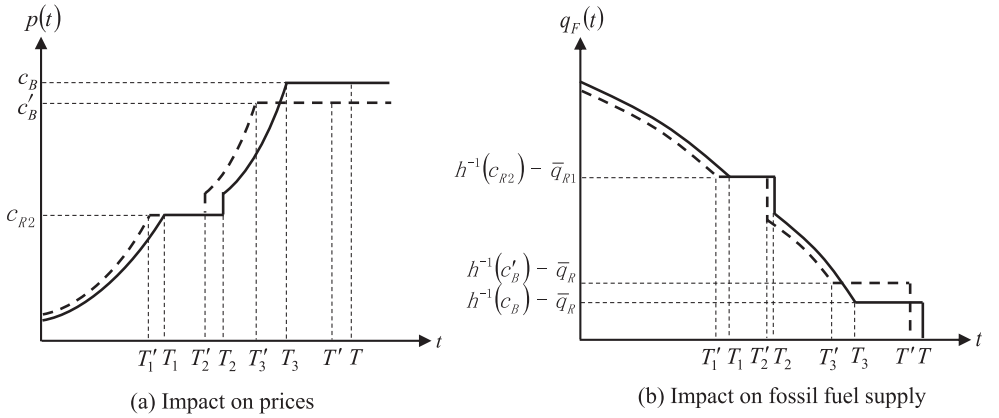


Fig. 6. Impacts of backstop price subsidies: monopoly.

flat and coincide with the residual demand at $p = c_{R2}$ (RD2) and $p = c_B$ (RD4): at these two price levels, the residual demand curve is flat so that the monopolist can increase its supply without reducing the energy price, since R2 or the backstop firms are indifferent about how much they supply at these prices (cf. (3) and (4)) and will simply "make up" the rest of the total demand. In other words, the monopolist can increase its supply (up to the total demand) without decreasing the energy price, causing the MR to equal the energy price. These MR curves are labeled as Seg2 and Seg4 in Fig. 5(b). Thus when R2 or backstop just becomes competitive, the marginal revenue jumps from $h'q_F + h$ up to h.

The monopolist chooses its output to maximize the Hamiltonian in (12) by comparing the marginal revenue with AMC, which equals $c_F + \mu e^{rt}$. In Fig. 5(b), we plot the MR curves against various levels of AMC: $AMC(t)$ is a horizontal line and continuously shifts up over time. The marginal revenue curve is not continuous, so that the equilibrium might occur at interior or corner solutions. We divide the type of solutions, as well as the associated equilibrium price and quantity paths into several stages: Fig. 5(b) shows representative levels of AMC corresponding to these stages, and Fig. 6 (solid curves) illustrates the equilibrium price and quantity paths.

During the first stage $t \in [0, T_1)$, where T_1 is such that $AMC(T_1) = MR_1$ in Fig. 5(b), $p(t) < c_{R2}$ and R2 is not competitive. The optimal q_F is given by an interior solution at the intersection of AMC and Seg 1 of the MR curve:

$$h'\left(q_F(t) + \overline{q}_{R1}\right) q_F(t) + h\left(q_F(t) + \overline{q}_{R1}\right) = c_F + \mu e^{rt}, \quad t \in [0, T_1). \tag{14}$$

During this stage, R1 is supplied at its full capacity and fossil fuels supply the residual demand. R2 and the backstop do not enter the market. The corresponding price $p(t)$ can be read off in Fig. 5(a): given quantity $q_F(t)$, the price is read from the residual demand curve (RD1). As shown in Fig. 6, $p(t)$ increases (up to C_{R2}) and $q_F(t)$ decreases within this stage.

At $t = T_1$, $p(T_1) = c_{R2}$ so that R2 become competitive. As discussed earlier, the monopolist's (residual) marginal revenue jumps up to Seg2 while $AMC(t)$ still continuously increases. Therefore, right after T_1, the marginal revenue, which is equal to c_{R2}, is higher than $AMC(t)$ for a while, and the optimal q_F takes a corner solution: $q_F(t) = h^{-1}(c_{R2}) - \overline{q}_{R1}$, so that the monopolist

supplies the entire residual market with R1 supplying at its capacity. During this period, the monopolist, as the Stackelberg leader, floods the market and staves off R2.

If the monopolist raises the market price above c_{R2}, R2 will supply at its full capacity, reducing the supply of q_F by $\overline{q}_{R2}$. The monopolist needs to weigh the output loss against gains from raising the energy price. As $AMC(t)$ rises, the profit margin of flooding the market, which equals $p(t) - AMC(t) = c_{R2} - AMC(t)$, decreases. At a certain point of time, it pays to raise the price above c_{R2} and let R2 into the market: the increased profit margin more than offsets the reductions in market share. [7] In fact, as shown in Fig. 5(b), there is a period of time during which $AMC(t)$ remains between $\left[MR_2, c_{R2}\right]$ and still intersects with Seg3 of the MR curve. Then there are two possible solutions for $q_F(t)$: the corner solution as before and the interior solution determined by the intersection of Seg3 with AMC (t). As shown in Wang and Zhao (2013), there is a time T_2 before $AMC(t)$ reaches c_{R2} so that at $t = T_2$, the monopolist switches to the interior solution, energy price jumps up from c_{R2}, R2 supply jumps from zero to its full capacity $\overline{q}_{R2}$, and consequently the fossil fuel supply jumps down. The switch time T_2 is determined by

$$q_F\left(T_2\right)\left[h\left(q_F\left(T_2\right)+\overline{q}_R\right)-c_F-\mu e^{rT_2}\right]=\left[h^{-1}\left(c_{R2}\right)-\overline{q}_{R1}\right]\left(c_{R2}-c_F-\mu e^{rT_2}\right) \tag{15}$$

where $q_F\left(T_2\right)$ is the residual demand for fossil fuels at T_2 at the interior solution. Equation (15) states that at T_2 the Hamiltonian associated with the interior solution (the left hand side) should equal that associated with the corner solution (the right hand side). In Fig. 6, both the energy price and the fossil fuel supply remain constant during $[T_1, T_2]$.

Summary. *When energy price reaches c_{R2} at T_1, the monopolist will stave off R2 for a while by flooding the market and keeping the energy price flat at c_{R2}. Eventually, at $T_2 > T_1$, the monopolist lets the energy price jump up above C_{R2}. The monopolist's supply jumps down while that of R2 jumps up to its full capacity.*

During stage three with $t \in \left[T_2, T_3\right)$ where T_3 is such that $AMC(T_3) = MR_3$ in Fig. 5 (b), R1 and R2 are supplied at their full capacities and $q_F(t)$ is determined by an interior solution equating the marginal revenue (Seg3) to AMC:

$$h'\left(q_F(t)+\overline{q}_R\right)q_F(t)+h\left(q_F(t)+\overline{q}_R\right)=c_F+\mu e^{rt},\quad t\in[T_2,T_3). \tag{16}$$

The corresponding energy price $p(t)$ again is read off the residual demand curve (RD3) in Fig. 5(a). As $AMC(t)$ rises, $p(t)$ continuously increases and $q_F(t)$ continuously decreases, until T_3 when the energy price reaches c_B (Fig. 6). As the backstop becomes competitive, the marginal revenue jumps up to Seg4 in Fig. 5(b), exceeding $AMC(t)$. The monopolist again chooses the corner solution and floods the market, staving the backstop from the market for a certain time period. It does so until its stock is exhausted at T. For $t \in [T_3, T)$, $p(t) = c_B$ and the fossil fuel supply is given by

$$q_F(t)=h^{-1}\left(c_B\right)-\overline{q}_R,\quad t\in[T_3,T). \tag{17}$$

Intuitively, since the energy price cannot exceed c_B, any delay of fossil fuel extraction would incur the interest cost without any benefit. Therefore, during this stage the monopolist would extract its stock as soon as possible, i.e., it produces at the maximum rate given in (17). This pattern of staving off backstops by a monopolist was first established in Hoel (1978).

During the final stage, $t \in [T, \infty)$, the energy price remains constant at c_B, $q_F(t) = 0$, $q_{R1}(t) = \overline{q}_{R1}$, $q_{R2}(t) = \overline{q}_{R2}$ and the backstop supplies the rest of the demand at $h^{-1}\left(c_B\right) - \overline{q}_R$. Since at the exhaustion time T, $p(T) = h(q_F(T) + q_R(T) + q_B(T)) = c_B$, equation (13) implies

$$c_B = c_F + \mu e^{rT}. \tag{18}$$

The equilibrium price and quantity paths are fully characterized by $\left\{\mu, T_1, T_2, T_3, T, q_F\left(T_2\right)\right\}$, which are determined by (18), (15) and

$$\int_0^{T_1} q_F(t)\,dt+\left[h^{-1}\left(c_{R2}\right)-\overline{q}_{R1}\right]\left(T_2-T_1\right)+\int_{T_2}^{T_3} q_F(t)\,dt+X_{T_3}=X_0 \tag{19}$$

$$h'\left(h^{-1}\left(c_{R2}\right)\right)\left[h^{-1}\left(c_{R2}\right)-\overline{q}_{R1}\right]+c_{R2}=c_F+\mu e^{rT_1} \tag{20}$$

$$h'\left(q_F\left(T_2\right)+\overline{q}_R\right)q_F\left(T_2\right)+h\left(q_F\left(T_2\right)+\overline{q}_R\right)=c_F+\mu e^{rT_2} \tag{21}$$

$$h'\left(h^{-1}\left(c_B\right)\right)\left[h^{-1}\left(c_B\right)-\overline{q}_R\right]+c_B=c_F+\mu e^{rT_3} \tag{22}$$

Equation (19) is the resource exhaustion condition for fossil fuels, where the fossil fuel supply, $q_F(t)$, is derived from (14) and (16), and X_{T_3}, the fossil fuel stock at T_3, is independent of the initial stock X_0.[8] Equations (20)–(22) are versions of (14) at times T_1, T_2 and T_3 respectively, which are the optimal conditions that equate the marginal revenues at these times with the corresponding augmented marginal costs.

[7] For intuition, think about the extreme case where $AMC(t)$ has risen to C_{R2}. If the monopolist still staves off R2 by setting $p(t) = c_{R2}$, its profit margin drops to zero. This is clearly suboptimal.

[8] From (18) and (22), we know that $T - T_3$ is given by $T - T_3 = (1/n)\ln\left[(c_B - c_F)/(h'\left(h^{-1}\left(c_B\right)\right)\left(h^{-1}\left(c_B\right)-\overline{q}_R\right)+c_B-c_F)\right]$, which is independent of X_0. During the time interval $[T_3, T)$, the fossil fuel supply is a constant given in (17). The remaining fossil fuel stock at T_3, X_{T_3}, must be just enough to last this time interval. Thus, $X_{T_3} = \left(h^{-1}\left(c_B\right)-\overline{q}_R\right)\cdot(T-T_3)$, which is independent of initial stock X_0.

3.2. Impacts of renewable energy policies

Given the equilibrium paths of fossil fuel prices and supplies determined above, we next study how these paths respond to the renewable energy policies.

Proposition 2. *Suppose the fossil fuels are supplied by a monopolist. Then*

(1) $\partial\mu/\partial c_B < 0$; $\partial p(t)/\partial c_B < 0$ *and* $\partial q_F(t)/\partial c_B > 0$ *for* $t < T_1$; $\partial T_i/\partial c_B > 0$, $i = 1, 2, 3$; *and* $\partial T/\partial c_B > 0$: *backstop price subsidies raise the value of fossil fuels, raises the energy price and reduces fossil fuel production* $q_F(t)$ *in early periods (for* $t < T_1$*), and speed up the exhaustion of fossil fuels, leading to ambiguous climate change effects.*

(2) $\partial\mu/\partial c_{R2} < 0$; $\partial p(t)/\partial c_{R2} < 0$ *and* $\partial q_F(t)/\partial c_{R2} > 0$ *for* $t < T_1$; $\partial T_i/\partial c_{R2} > 0$, $i = 1, 3$; *and* $\partial T/\partial c_{R2} > 0$: *R2 price subsidies raise the value of fossil fuels, raise energy price and reduce fossil fuel production* $q_F(t)$ *in early periods (for* $t < T_1$*), and speed up the exhaustion of fossil fuels, leading to ambiguous climate change effects.*

(3) $\partial\mu/\partial\overline{q}_{R2} > 0$; $\partial p(t)/\partial\overline{q}_{R2} > 0$ *and* $\partial q_F(t)/\partial\overline{q}_{R2} < 0$ *for* $t < T_1$; $\partial T_1/\partial\overline{q}_{R2} < 0$, $\partial T/\partial\overline{q}_{R2} < 0$, *and the signs of* $\partial T_2/\partial\overline{q}_{R2}$ *and* $\partial T_3/\partial\overline{q}_{R2}$ *are ambiguous: R2 capacity expansion policies raise the value of fossil fuels, raise energy price and reduce fossil fuel production* $q_F(t)$ *in early periods (for* $t < T_1$*), and speed up the exhaustion of fossil fuels, leading to ambiguous climate change effects.*

(4) *Suppose the energy demand function is linear. Then* $\partial\mu/\partial\overline{q}_{R1} < 0$; $\partial p(t)/\partial\overline{q}_{R1} < 0$ *and* $\partial q_F(t)/\partial\overline{q}_{R1} < 0$ *for* $t < T_1$; $\partial T_i/\partial\overline{q}_{R1} > 0$, $i = 1, 2, 3$; *and* $\partial T/\partial\overline{q}_{R1} > 0$: *R1 capacity expansion policies reduce the value of fossil fuels, reduce both energy price and fossil fuel supply* $q_F(t)$ *for early periods (for* $t < T_1$*), and delay the exhaustion of fossil fuels, leading to climate friendly effects.*

Proposition 2(1) generalizes Hoel (1978), which studies an energy market facing a constant elasticity demand without capacity constrained renewables. Fig. 6 illustrates the impacts of the backstop price subsidies on energy prices and quantities. Opposite to the case of perfect competition (cf. Proposition 1 (1)), the monopolist fossil fuel owner *raises*, rather than reduces, energy prices in response to backstop cost reduction in periods before the backstop becomes competitive. This might seem surprising given that the backstop is a perfect substitute for fossil fuels. To understand the intuition, note that the monopolist, unlike a competitive producer, always has incentives to reduce its output in order to raise energy prices. This incentive is "mitigated" by the inherent dynamic nature of its decision problem: current extraction reductions will necessarily lead to future extraction increases, and current price hikes have to be balanced against future price reductions. The current vs. future trade-off is affected by, among other factors, the relative elasticities of the residual demand function facing the monopolist in different periods. Other things equal, the monopolist has incentives to supply more in periods with higher residual demand elasticities because it is more difficult to raise prices during these periods - it has to cut its production by a larger amount. During period $[T_3, T)$, the residual demand elasticity is infinite, and as a result the monopolist extracts the maximum possible amount, effectively staving off the backstop energy from the market. As c_B decreases, this period of infinite residual demand elasticity starts earlier (Fig. 6(a)): T_3 decreases to T_3' so that for period $[T_3', T_3]$, the residual demand elasticity increases from finite levels to infinite after the policy change. Further, since $p(t) = c_B' < c_B$ during $t \geq T_3'$, the lower backstop cost implies that the monopolist needs to produce more in order to flood the market. In response to the two changes, the monopolist has to reduce its extraction in early periods to reserve enough resources to enable it to increase its extraction for periods $t \geq T_3'$.

Proposition 2(1) and Fig. 6(b) show that, although backstop price subsidies reduce the early use of fossil fuels, the stock of fossil fuels is also exhausted earlier. The net effect of such policies on global climate change is ambiguous, allowing the possibility that backstop policies help mitigate climate change if the damages from increased carbon emissions in the future are more than offset by gains from reduced carbon emissions in early periods. Further, the effects under monopoly differs sharply from the case of perfect competition: with the existence of market power, backstop price subsidies are not necessarily subject to the Green Paradox.

Proposition 2(2) shows that the impacts of R2 price subsidies are similar to those of backstop price subsidies. Fig. 7 illustrates the impacts on the price and quantity paths. The intuition is again similar to that in Proposition 2 (1). As c_{R2} decreases, two changes occur related to the residual demand elasticities: (i) the period of infinite elasticity when the monopolist floods the market to stave off R2 occurs earlier, and (ii) the monopolist needs to produce more in order to stave off R2 since the energy price, which equals the cost of R2, is now lower. Both changes imply that the monopolist has incentives to reduce its output before R2 become competitive, so that it has enough stock of resources to raise its output during the "stave-off" period $[T_1, T_2)$. In fact, as shown in Fig. 7(b), the monopolist's output also decreases after T_2 due to the increased production during $[T_1, T_2)$.

Proposition 2(3) and Fig. 8 show the effects of capacity expansion policies for R2, and again the impacts depend on how cross-period comparisons of the residual demand elasticities are affected. As R2's capacity expands, one segment of the residual demand in Fig. 5(a), RD3, shifts in. As is commonly known, demand elasticities increase when demand curves shift in parallelly. For example, in the case of linear demand, the elasticity equals $-(dq_F/dp)(p/q_F)$ where the slope dq_F/dp is a constant. As $\overline{q}_{R2}$ rises, the residual demand curve shifts further in, reducing q_F thereby raising the ratio p/q_F and thus the elasticity. Since the residual demand curve is unaltered for $p < c_{R2}$, the net impact of a higher $\overline{q}_{R2}$ is that the residual demand elasticities are higher in future periods but remain unchanged in early periods. Then the monopolist will extract less in early periods (before T_1) and more in future periods.

Proposition 2(4) shows the effects of capacity expansion policies for R1. Different from the case of R2, the expansion of

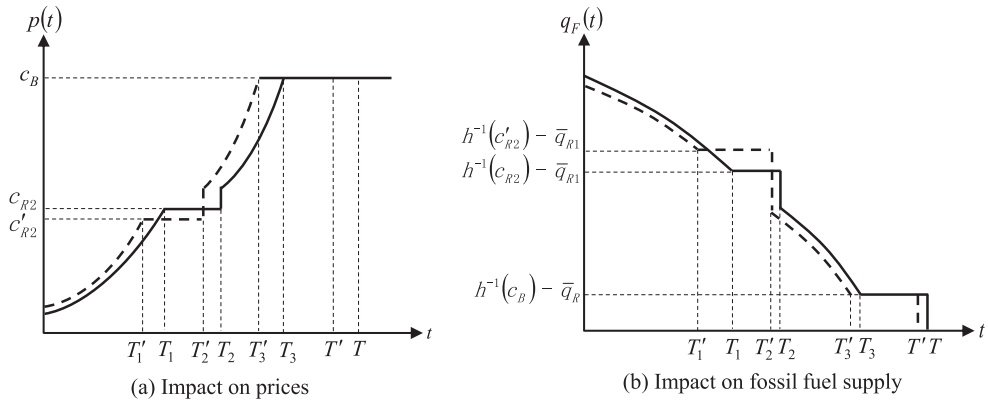


Fig. 7. Impacts of R2 price subsidies: monopoly.

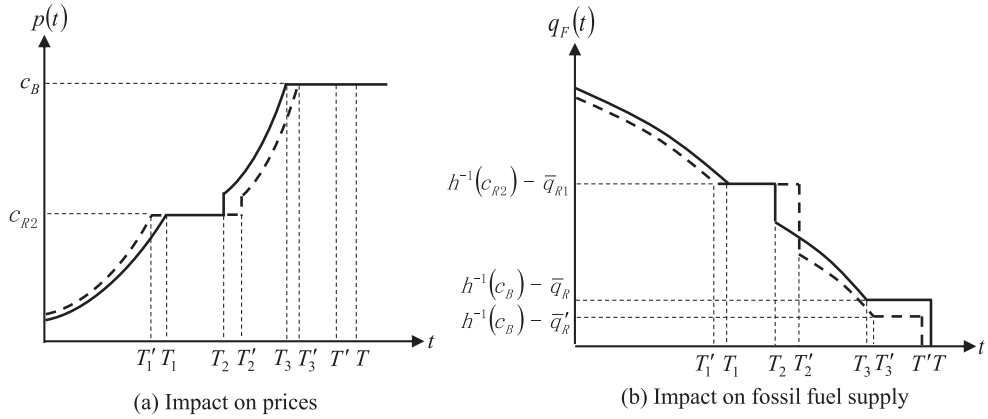


Fig. 8. Impacts of R2 capacity expansion policies: monopoly.

R1's capacity shifts inward the residual demand curves in both the early and future periods (i.e., both RD1 and RD3). Let $\epsilon = -h(Q) / \left[Qh'(Q)\right]$ be the elasticity of the total energy demand function. When $h(\cdot)$ is linear, the residual demand elasticity is

$$-\frac{dq_F}{dp}\frac{p}{q_F} = -\frac{1}{h'(Q)}\frac{p}{Q}\frac{Q}{q_F} = \epsilon\frac{Q}{q_F},$$

where the first equality follows since the residual and total demand curves have the same slope for linear demands. Evidently the residual demand elasticity is decreasing in the market share of fossil fuels q_F/Q. R1 capacity expansion policies reduce the market share of fossil fuels in all periods. However, because the fossil fuel supply is larger in early periods than in future periods, the reduction of the market share of fossil fuels in early periods is less than that in future periods, i.e., the residual demand elasticities are raised less in early periods than in future periods. Therefore, at least for the case of linear demand, capacity expansion in R1 will lead the monopolist to extract less in early periods and more in future periods. Note that since the increased supply of R1 offsets the supply reduction of fossil fuels, the energy price declines in early periods. Fig. 9 shows the changes in price and quantity paths in response to capacity expansion of R1. Current production of fossil fuels is delayed to future periods and the fossil fuel stock is exhausted at a later time. Thus, R1 capacity expansion policies are indeed climate friendly.

4. The role of capacity constraints and market power

Table 1 summarizes the "climate friendliness" of the various renewable energy policies under the two types of market structures, where "+" and "−" represent climate friendly and unfriendly impacts respectively. A policy is climate friendly if its impacts are positive in terms of both current fossil fuel production (i.e., it reduces current production) and exhaustion time (i.e., it delays exhaustion of fossil fuels), and is subject to the Green Paradox if both impacts are negative. Thus, capacity expansion policies for R1 are climate friendly regardless of the market structure, and backstop price subsidies are subject to the Green Paradox when the fossil fuel market is competitive. The results indicate that *when both exhaustion time and early production of fossil fuels are considered, few policies have unambiguous impacts, and most of them are not subject to the qualitative definisions of the*

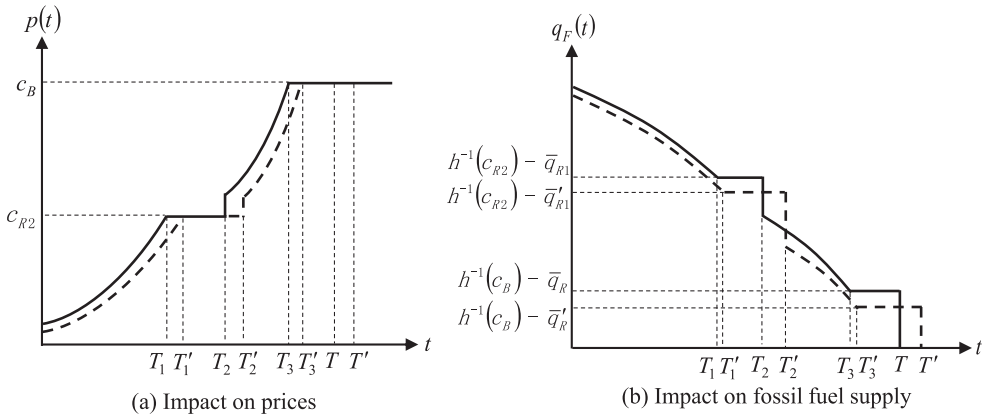


Fig. 9. Impacts of R1 capacity expansion policies: monopoly.

Green Paradox. Detailed and careful numerical studies are thus needed to evaluate the net climate impacts of renewable energy policies.

Comparison of the climate impacts of backstop and R2 price subsidies indicates that capacity constraints play a significant role in determining the policy effects in the case of perfect competition. Although backstop price subsidies are subject to the Green Paradox, R2 price subsidies can delay the exhaustion of fossil fuels, which is a climate friendly effect. Under monopoly, comparing Figs. 6(b) and 7(b) shows that backstop price subsidies tend to move fossil fuel supplies to the far future (after T_3) while R2 price subsidies move the supplies to the intermediate future (between T_1 and T_2), including moving fossil fuel consumption from after T_2 to the intermediate future $[T_1, T_2)$. The difference is again due to the capacity constraints of R2.[9]

The impacts of a capacity expansion policy are sensitive to whether or not the renewable energy is already competitive. While the capacity expansion of R1 is always climate friendly, the capacity expansion of R2 leads to more current fossil fuel production under perfect competition, and speeds up the exhaustion of fossil fuels under monopoly. That is, *future* capacity expansion of not-yet-competitive capacity constrained renewables can lead to adverse effects while *current* capacity expansion of already competitive renewables is always climate friendly.

Table 1 also shows that the climate change impacts of renewable policies are sensitive to the market structure of fossil fuels. The climate impacts of R2 policies under competition, including price subsidies and capacity expansion, are opposite to those under monopoly. While backstop price subsidies raise current fossil fuel supply under competition, the opposite is true under monopoly. Only when the renewable energy is already competitive, as in the case of R1, are the impacts similar across competition and monopoly.

The existence of the "stave-off" periods under monopoly is a major factor driving the difference between competition and monopoly. As shown in Fig. 6(b), the reason that backstop price subsidies under monopoly reduce early period fossil fuel supply is that the monopolist needs to produce more during the "stave-off" period when it floods the market to drive out the backstop. Similarly in the case of R2 price subsidies, as shown in Fig. 7(b), increased fossil fuel supply during the "stave-off" period causes the monopolist to reduce its production in earlier periods and leads to earlier exhaustion of the fossil fuel stock. In the case of capacity expansion of R2, Fig. 8(b) shows that it is again the increased fossil fuel supply during the "stave-off" period that causes reduced supply in early periods and earlier exhaustion time. The existence of "stave-off" periods is not merely a theoretical conjecture: some argue that OPEC intensionally keeps oil prices low to keep renewable energies off the market (Indiviglio, 2010), and many renewable energies remain "almost" competitive for prolonged time periods. What we show in this paper is that the "stave-off" periods in fact play a crucial role in determining the climate impacts of renewable policies.

5. Discussion and conclusions

This paper studies the long-term impacts of renewable energy policies on energy prices, fossil fuel supply and thus carbon emissions and climate change, highlighting the role of capacity constraints of renewable energies and the market power in the fossil fuel sector. We show that once capacity constraints and imperfect competition are accounted for, the impacts of renewable energy policies on early fossil fuel extraction and on its exhaustion time can be opposite to each other. Traditional notions of (weak) Green Paradox that are based on only one of these factors have to be enhanced. We extend the literature and define climate friendliness (resp. Green Paradox) as reducing (resp. raising) current fossil fuel use as well as delaying (resp. speeding up) fossil fuel exhaustion time.

[9] To the extent that capacity constraints represent the shape of the production costs of renewable energies, the sensitivity to capacity constrains is similar to the sensitivity to production cost functions found in Grafton et al. (2012).

We find that capacity expansion of renewable energies that are already competitive is climate friendly. But for renewable energies that are not yet competitive, the climate change impacts of their support policies are often ambiguous and are sensitive to the existence of capacity constraints and to the fossil fuel market structure. Backstop price subsidies are subject to the Green Paradox under perfect competition, but does reduce current fossil fuel use under monopoly. Supports for capacity constrained not-yet-competitive renewables under perfect competition lead to more current fossil fuel supply but delays fossil fuel exhaustion time, and these effects are reversed under monopoly. A critical factor determining the climate impacts under monopoly is the monopolist's practice of flooding the market to stave off the renewables when they just become competitive.

Our findings have important implications for the debate on the carbon footprints of renewable energies, especially capacity constrained renewable such as sugarcane or corn ethanol, as well as for renewable energy policy design. Despite the controversy over indirect land use changes associated with corn based ethanol, the dynamic fuel market effects of expanding its production are climate friendly given that sugarcane/corn ethanol in certain production regions is already competitive. This finding favors quantity policies and R&D subsidies that expand the feedstock for sugarcane/corn ethanol production. When the fossil fuel sector is under monopoly, policy supports for renewable energies that are not yet competitive can reduce current fossil fuel supplies, and can have positive climate impacts if concerns about short-term carbon emissions dominate concerns about long-term carbon emissions associated with earlier depletion of fossil fuels.

We made a number of simplifying assumptions in the paper, including linear production costs for all energies. Allowing the extraction cost of fossil fuels to be convex and stock dependent will not affect our major conclusions regarding the role of capacity constraints and market power. When fossil fuels are competitively supplied, renewable energies inevitably reduce the in-situ value of fossil fuel stocks regardless of the extraction cost structure, so that the qualitative impacts of renewable energies remain unchanged as the cost structure varies. In the case of fossil fuel monopoly, the driving force in determining the climate change impacts of fossil fuels is the existence of "stave-off" periods when the monopolist floods the market to prevent the immediate entry of renewable energies. Wang and Zhao (2013) shows that such "stave-off" periods still exist when fossil fuel extraction costs are convex and stock dependent. Consequently climate change impacts of renewable policies remain sensitive to market structures under convex and stock dependent extraction costs.

Allowing stock dependent extraction costs does add one important effect of renewable policies that we do not study, namely the economic exhaustion of fossil fuels. Suppose fossil fuel extraction costs are decreasing in their stock levels. Then the stocks might not be exhausted and renewable subsidies might have an additional benefit of leaving more fossil fuels in the ground without ever being extracted (van der Ploeg and Withagen (2012)). As we discussed earlier (cf. Footnote 6), to limit global temperature increase from preindustrial levels to 2 °C, future carbon emissions should be limited to about 1000 Gt, implying that the "economic exhaustion" of fossil fuels has to occur earlier than their physical exhaustion. We can incorporate this important factor in two ways. First, we can be extremely confident that the 2 °C goal will be achieved and simply set the initial fossil fuel stock as the maximum amount that can be extracted to reach this goal, namely an amount equivalent to 1000 $GtCO_2$. Then every conclusion of our model still holds. Second, we can explicitly model stock dependence, showing that renewable subsidies could have the additional benefit of speeding up the economic exhaustion of fossil fuels.

In this paper we choose to model capacity constrained renewable production costs as linear but subject to capacity constraints, the setup being an extreme version of a convex cost function. This representation enables us to distinguish price subsidies from quantity policies such as mandatory quantity or blending requirements. We showed that the two kinds of policies can lead to qualitatively different climate impacts even though both serve to "push down" the production cost curve. This distinction would have been lost if we model a generic convex cost function. Our setup is by no means only a theoretical curiosity but represents real world cost functions for many renewables. At the very minimum, our setup approximates the real world better than the often used alternative of quadratic cost functions.

We considered two extreme versions of fossil fuel market structures, perfect competition and monopoly, to highlight the sensitivity of policy impacts to market forces. The literature has studied two additional, and more realistic, market structures, oligopoly with a limited number of fossil fuel producers, and cartel-fringe where a cartel such as OPEC coexists with price-taking fringe fossil fuel firms. The additional realism is important if one attempts to quantitatively assess the climate impacts of renewable energies, e.g., through calibrated cost and demand functions. It is less important in our study since our focus is on the qualitative impacts, i.e., whether renewable policies can move fossil fuel supplies to the future and/or delay their exhaustion.

An important and interesting extension of our paper is to conduct a careful numerical study of the effects of the renewable policies that incorporates not only more realistic fossil fuel market structures but more importantly discounting and the decay of atmospheric CO_2. The numerical approach is necessary because, as we have demonstrated, the effects of many renewable policies on early fossil fuel extraction and on the exhaustion date are often opposite to each other. Even when two policies have qualitatively similar impacts on the two indicators of climate friendliness, their effects on the paths of fossil fuel supply can differ in terms of when increased supply would take place. The net effects then depend on the intertemporal comparisons of the damages, which in turn depend critically on discounting and CO_2's decay rate.

A. Starting fossil fuel stock X_0

In this section we identify the two threshold values of fossil fuel stock $X_{0,l}$ and $X_{0,h}$ ($X_{0,l} < X_{0,h}$) such that for any $X_0 \in [X_{0,l}, X_{0,h}]$, the condition $c_{R1} < p(0) < c_{R2}$ holds. Specifically, $X_{0,l}$ (or $X_{0,h}$) is the value that guarantees $p(0) = c_{R2}$ (or c_{R1}). Below we define the two stock values under the two market structures of perfect competition and monopoly.

Competitive fossil fuel market. By setting $\Gamma_1 = 0$ in (8), (9) and (10), we can define $X_{0,l}$ by

$$X_{0,l} = \int_0^y h^{-1}\left(c_F + \left(c_{R2} - c_F\right)e^{rt}\right)dt - \overline{q}_R y, \tag{23}$$

where y is determined by $c_F + \left(c_{R2} - c_F\right)e^{ry} = c_B$. Note that if $X_0 = X_{0,l}$, the current shadow value of fossil fuels equals $c_{R2} - c_F$ and $p(0) = c_{R2}$. Similarly

$$X_{0,h} = \int_0^y h^{-1}\left(c_F + \left(c_{R1} - c_F\right)e^{rt}\right)dt - \overline{q}_{R1} y - \overline{q}_{R2}(y - z) \tag{24}$$

where y and z are respectively determined by $c_F + \left(c_{R1} - c_F\right)e^{ry} = c_B$ and $c_F + \left(c_{R1} - c_F\right)e^{rz} = c_{R2}$.

Monopolistic fossil fuel market. We define $X_{0,l}$ by

$$X_{0,l} = X_{T_3} + \left[h^{-1}\left(c_{R2}\right) - \overline{q}_{R1}\right]y + \int_y^z q_F(t)\,dt \tag{25}$$

where, given $\mu = h'\left(h^{-1}\left(c_{R2}\right)\right)\left[h^{-1}\left(c_{R2}\right) - \overline{q}_R\right] + c_{R2} - c_F$, $q_F(t)$ is determined by (16), z is the solution for T_3 in (22), and y is the solution for T_2 in (15) and (21). Similarly, the upper bound of the stock size is

$$X_{0,h} = X_{T_3} + \left[h^{-1}\left(c_{R2}\right) - \overline{q}_{R1}\right](y - x) + \int_0^x q_F(t)\,dt + \int_y^z q_F(t)\,dt \tag{26}$$

where, given $\mu = h'\left(h^{-1}\left(c_{R1}\right)\right)\left[h^{-1}\left(c_{R1}\right) - \overline{q}_{R1}\right] + c_{R1} - c_F$, $q_F(t)$ in the first and second integration is determined by (14) and (16) respectively, x solves T_1 in (20), z is the solution for T_3 in (22), and y is the solution for T_2 in (15) and (21).

B. Proofs

Proof of Proposition 1. *Step 1:* We first prove the effects on λ, Γ_1 and Γ in the Proposition. Note that the equilibrium conditions in (8)–(10) include three equations with three endogenous variables $\{\lambda, \Gamma_1, \Gamma\}$. Totally differentiating (8)–(10), we obtain

$$\begin{pmatrix} \int_0^\Gamma \frac{e^{rt}}{h'(q(t))}dt & \overline{q}_{R2} & h^{-1}\left(c_B\right) - \overline{q}_R \\ e^{r\Gamma_1} & r\lambda e^{r\Gamma_1} & 0 \\ e^{r\Gamma} & 0 & r\lambda e^{r\Gamma} \end{pmatrix}\begin{pmatrix} d\lambda \\ d\Gamma_1 \\ d\Gamma \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix}dc_B + \begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix}dc_{R2} + \begin{pmatrix} \Gamma \\ 0 \\ 0 \end{pmatrix}d\overline{q}_{R1} + \begin{pmatrix} \Gamma - \Gamma_1 \\ 0 \\ 0 \end{pmatrix}d\overline{q}_{R2} \tag{27}$$

where $q(t) = h^{-1}\left(\lambda e^{rt} + c_F\right)$. In deriving the first row on the left hand side of (27), we used the conditions of $p(t) = c_F + \lambda e^{rt}$ for $t \le \Gamma$ and $p(\Gamma) = c_F + \lambda e^{r\Gamma} = c_B$.

To prove Part (1) of the Proposition, we apply Cramer's rule to (27) to obtain

$$\begin{aligned} \frac{\partial\lambda}{\partial c_B} &= -r\lambda e^{r\Gamma_1}\left[h^{-1}\left(c_B\right) - \overline{q}_R\right]/\Phi > 0, \\ \frac{\partial\Gamma_1}{\partial c_B} &= e^{r\Gamma_1}\left[h^{-1}\left(c_B\right) - \overline{q}_R\right]/\Phi < 0, \\ \frac{\partial\Gamma}{\partial c_B} &= \left[r\lambda e^{r\Gamma_1}\int_0^\Gamma \frac{e^{rt}}{h'(q(t))}dt - \overline{q}_{R2}e^{r\Gamma_1}\right]/\Phi > 0, \end{aligned} \tag{28}$$

where Φ is the determinant of the square matrix in (27), given by

$$\Phi = r\lambda e^{r(\Gamma_1+\Gamma)}\left[r\lambda\int_0^\Gamma \frac{e^{rt}}{h'(q(t))}dt - h^{-1}\left(c_B\right) + \overline{q}_{R1}\right] < 0. \tag{29}$$

The inequalities in (28) and (29) follow from $h'(\cdot) < 0$ and $h^{-1}(c_B) > \overline{q}_R > \overline{q}_{R1}$.

Following the same approach, we obtain the effects of R2 price subsidies:

$$\begin{aligned} \frac{\partial\lambda}{\partial c_{R2}} &= -\overline{q}_{R2}r\lambda e^{r\Gamma}/\Phi > 0, \\ \frac{\partial\Gamma_1}{\partial c_{R2}} &= e^{r\Gamma}\left[r\lambda\int_0^\Gamma \frac{e^{rt}}{h'(q(t))}dt - h^{-1}\left(c_B\right) + \overline{q}_R\right]/\Phi > 0, \end{aligned}$$

$$\frac{\partial \Gamma}{\partial c_{R2}} = \overline{q}_{R2} e^{r\Gamma}/\Phi < 0;$$

the effects of capacity expansion policies for R2:

$$\frac{\partial \lambda}{\partial \overline{q}_{R2}} = (r\lambda)^2 e^{r(\Gamma_1+\Gamma)} \left(\Gamma - \Gamma_1\right)/\Phi < 0,$$

$$\frac{\partial \Gamma}{\partial \overline{q}_{R2}} = \frac{\partial \Gamma_1}{\partial \overline{q}_{R2}} = -\left(\Gamma - \Gamma_1\right) r\lambda e^{r(\Gamma_1+\Gamma)}/\Phi > 0;$$

and the effects of capacity expansion policies for R1:

$$\frac{\partial \lambda}{\partial \overline{q}_{R1}} = (r\lambda)^2 e^{r(\Gamma_1+\Gamma)}\Gamma/\Phi < 0, \ \frac{\partial \Gamma}{\partial \overline{q}_{R1}} = \frac{\partial \Gamma_1}{\partial \overline{q}_{R1}} = -\Gamma r\lambda e^{r(\Gamma_1+\Gamma)}/\Phi > 0. \tag{30}$$

Step 2: We next prove the effects of renewable policies on fossil fuel supply $q_F(t)$. From (6), we know

$$\frac{\partial q_F(t)}{\partial x} \propto -\frac{\partial \lambda}{\partial x}, \quad x \in \{c_B, c_{R2}, \overline{q}_{R2}\}, \quad t \in [0, \Gamma_1].$$

Thus, backstop price subsidies, R2 price subsidies and R2 capacity expansion policies will increase the fossil fuel supply in this early period as they depress the value of λ. These results, together with the results in Step 1, prove Parts (2) and (3) of the Proposition, as well as Part (1) of the Proposition for $t < \Gamma_1$. For $t \geq \Gamma_1$, $q_F(t) = h^{-1}(c_F + \lambda e^{rt}) - \overline{q}_R$ (cf. (7)). Again, since $\partial\lambda/\partial C_B > 0$, we know $\partial q_F(t)/\partial C_B < 0$. Further, since $\partial\Gamma_1/\partial c_B < 0$, we know that as c_B decreases, $q_F(t)$ increases for all $t \geq 0$, as show in Fig. 1.

To prove Part (4) of the Proposition, we apply the implicit function theorem to (6) and (7) to obtain

$$\frac{\partial q_F(t)}{\partial \overline{q}_{R1}} = \frac{e^{rt}\partial\lambda/\partial \overline{q}_{R1}}{h'(q(t))} - 1,$$

where $q(t) = h^{-1}\left(\lambda e^{rt} + c_F\right)$. Further by substituting in $\partial\lambda/\partial\overline{q}_{R1}$ from (30) and using (29), we obtain

$$\frac{\partial q_F(t)}{\partial \overline{q}_{R1}} = \frac{e^{rt} r\lambda\Gamma}{h'(q(t))\left[r\lambda\int_0^\Gamma \frac{e^{rt}}{h'(q(t))}dt - h^{-1}\left(c_B\right) + \overline{q}_{R1}\right]} - 1. \tag{31}$$

Since $q(t)$ is decreasing in t, we know if the demand function is weakly convex, $h'(q(t))$ decreases in t and (31) implies that $\partial q_F(t)/\partial\overline{q}_{R1}$ monotonically increases in t. In order to show $\partial q_F(t)/\partial\overline{q}_{R1} < 0$ for small values of t, we first argue that

$$\partial q_F(t)/\partial \overline{q}_{R1} < 0 \quad \text{for positive measures of } t \text{ values in } [0, T]. \tag{32}$$

To see this, suppose on the contrary, $\partial q_F(t)/\partial\overline{q}_{R1} \geq 0$ for all $t \in [0, T]$. Since $\partial\Gamma_1/\partial\overline{q}_{R1} > 0$, $\partial\Gamma/\partial\overline{q}_{R1} > 0$, and $q(t)$ is decreasing in t, a higher $\overline{q}_{R1}$ would raise fossil fuel supply $q_F(t)$ for all periods, as well as delay the exhaustion time. This violates the resource exhaustion condition, establishing (32). Then, since $\partial q_F(t)/\partial\overline{q}_{R1}$ is increasing in time, and given that it has to be negative for some time periods (from (32)), it must be negative during early periods, proving Part (4) of the Proposition. ∎

Proof of Proposition 2. (I) Proof of Parts (1) - (3). We first establish a set of results that will be used in subsequent analysis.

Lemma 1. *The current value Hamiltonian $H(t)$ in (12) satisfies the following conditions:*

$$\frac{\partial H(t)}{\partial q_F(t)}\frac{dq_F(t)}{dt} = 0 \quad \textit{for all } t, \tag{33}$$

$$H(t) = r\int_t^T e^{-r(\tau-t)}\left[h(q_F(\tau) + q_R(\tau) + q_B(\tau))q_F(\tau) - c_F q_F(\tau)\right]d\tau \quad \textit{for all } t, \tag{34}$$

$$V(\cdot) = \frac{H(0) - H(T)}{r} = \frac{H(0)}{r} = \frac{h\left(q_F(0) + \overline{q}_{R1}\right)q_F(0) - c_F q_F(0) - \mu q_F(0)}{r}, \tag{35}$$

$$\frac{\partial H(0)}{\partial z} = \frac{\partial H(0)}{\partial q_F(0)}\frac{\partial q_F(0)}{\partial z} + \frac{\partial H(0)}{\partial \mu}\frac{\partial \mu}{\partial z} = -q_F(0)\frac{\partial \mu}{\partial z} \quad \textit{for any } z \in \left\{c_{R2}, c_B, \overline{q}_{R2}\right\}, \tag{36}$$

$$\frac{\partial H(0)}{\partial \overline{q}_{R1}} = q_F(0)\left[h'\left(q_F(0) + \overline{q}_{R1}\right) - \frac{\partial \mu}{\partial \overline{q}_{R1}}\right]. \tag{37}$$

To show (33), note that the first order condition on $q_F(t)$ is $\partial H(t)/\partial q_F(t) = 0$ and thus (33) is satisfied when the optimal $q_F(t)$ is an interior solution, i.e., when $t \in [0, T_1)$ and $t \in [T_2, T_3)$. When $t \in [T_1, T_2)$, the optimal $q_F(t) = h^{-1}(c_{R2}) - \overline{q}_{R1}$ (a corner

solution), and when $t \geq T_3$, the optimal $q_F(t) = h^{-1}(c_B) - \overline{q}_R$. In both cases, $q_F(t)$ is time invariant, so that $dq_F(t)/dt = 0$ and thus (33) is satisfied.

To show (34), we take the derivative of $H(t)$ in (12) with respect to t and obtain

$$\frac{dH(t)}{dt} = \frac{\partial H(t)}{\partial q_F(t)} \frac{dq_F(t)}{dt} - r\mu e^{rt} q_F(t) = -r\mu e^{rt} q_F(t) \tag{38}$$

where the second equality follows from (33). Thus, $\mu e^{rt} q_F(t) = -(1/r)\, dH(t)/dt$. Substituting this to (12), we obtain a differential equation in $H(t)$:

$$H(t) = h(\cdot) q_F(t) - c_F q_F(t) + \frac{1}{r} \frac{dH(t)}{dt},$$

the solution of which, given the boundary condition in (13), is (34).

The first equality in (35) follows from comparing the definition of $V(\cdot)$ in (11) and (34) with $t = 0$. The second equality follows since $H(T) = 0$ under the transversality condition (13), and the third equality follows from the definition of $H(\cdot)$ in (12).

The first equality in (36) follows since at time $t = 0$, the only variables affected by the exogenous parameters c_{R2}, c_B, and $\overline{q}_{R2}$ are $q_F(0)$ and μ. The second equality follows since $\partial H(0)/\partial q_F(0) = 0$, which is the first order condition on $q_F(0)$ (an interior solution at $t = 0$), and $\partial H(0)/\partial \mu = q_F(0)$ from (12).

The derivation of (37) is similar to that of (36), except for the additional term associated with $h'(\cdot)$, which follows since the inverse demand at $t = 0$ is given by $h(q_F(0) + \overline{q}_{R1})$.

We next prove Parts (1)–(3) of the Proposition in several steps.

Step 1: results related to the impacts on μ. As illustrated in Fig. 5, an increase in c_B and c_{R2} will raise the residual demand facing the monopolist, thereby relaxing the constraints (3) and (4) in the monopolist's optimization problem (11). In contrast, an increase in $\overline{q}_{R2}$ will reduce the residual demand, tightening the constraints facing the monopolist. Hence, the monopolist's payoff $V(\cdot)$ in (11) satisfies the following conditions: $\partial V(\cdot)/\partial c_B > 0$, $\partial V(\cdot)/\partial c_{R2} > 0$, and $\partial V(\cdot)/\partial \overline{q}_{R2} < 0$. These inequalities, together with $V(\cdot) = H(0)/r$ (cf. (35)), imply that $\partial H(0)/\partial c_B > 0$, $\partial H(0)/\partial c_{R2} > 0$, and $\partial H(0)/\partial \overline{q}_{R2} < 0$, which, from (36), in turn imply that

$$\frac{\partial \mu}{\partial c_B} < 0, \frac{\partial \mu}{\partial c_{R2}} < 0, \text{ and } \frac{\partial \mu}{\partial \overline{q}_{R2}} > 0, \tag{39}$$

proving the part of Proposition 2(1)–(3) related to the impacts on μ.

Step 2: results related to the impacts on p(t) and qF(t), t < T1. For $t < T_1$, $q_F(t)$ is governed by (14), the right hand side of which is increasing in μ and the left hand side of which is decreasing in $q_F(t)$ (since the revenue function is assumed to be concave in q_F, i.e., MR is decreasing in q_F). Thus, as μ decreases (or increases), $q_F(t)$ increases (or decreases), and $p(t) = h(q_F(t) + \overline{q}_{R1})$ decreases (or increases), proving the part of Proposition 2(1)–(3) related to the impacts on $q_F(t)$.

Step 3: results related to the impacts on switch times. The Proof proceeds in several substeps, each relating to one of Parts (1)–(3) of the Proposition.

Substep 3.1: Part (1) of the Proposition. From (18), we know

$$\frac{\partial T}{\partial c_B} = -\frac{1}{r\mu} \frac{\partial \mu}{\partial c_B} > 0,$$

where the inequality follows from (39). From (20), we know

$$\frac{\partial T_1}{\partial c_B} = -\frac{1}{r\mu} \frac{\partial \mu}{\partial c_B} > 0,$$

where the equality follows since the left hand side of (20) is independent of c_B, and the inequality follows from (39). Equations (15) and (21) form a system of equations with two variables, T_2 and $q_F(T_2)$. Applying the implicit function theorem, we obtain

$$\frac{\partial T_2}{\partial c_B} = -\frac{1}{r\mu} \frac{\partial \mu}{\partial c_B} > 0.$$

Finally, from (22), we know

$$\frac{\partial T_3}{\partial c_B} = \frac{1}{r\mu e^{rT_3}} \frac{\partial MR(T_3)}{\partial q_F(T_3)} \frac{\partial q_F(T_3)}{\partial c_B} - \frac{1}{r\mu} \frac{\partial \mu}{\partial c_B} > 0.$$

The equality follows since the left hand side of (22) is simply the marginal revenue $MR(T_3)$. The inequality follows from three facts: (i) $\partial \mu/\partial c_B < 0$ (cf. (39)), (ii) $\partial MR(T_3)/\partial q_F(T_3) < 0$ due to the concavity of the revenue function, and (iii) $\partial q_F(T_3)/\partial c_B < 0$ since $q_F(T_3) = h^{-1}(c_B) - \overline{q}_R$ and the demand function is downward slopping (i.e., $h'(\cdot) < 0$).

Substep 3.2: Part (2) of the Proposition. Adopting the same approach as in Substep 3.1, we can show

$$\frac{\partial T_3}{\partial c_{R2}} = \frac{\partial T}{\partial c_{R2}} = -\frac{1}{r\mu} \frac{\partial \mu}{\partial c_{R2}} > 0, \quad \frac{\partial T_1}{\partial c_{R2}} = \frac{1}{r\mu e^{rT_1}} \frac{\partial MR(T_1)}{\partial q_F(T_1)} \frac{\partial q_F(T_1)}{\partial c_{R2}} - \frac{1}{r\mu} \frac{\partial \mu}{\partial c_{R_2}} > 0,$$

using (18), (20) and (22). To prove $\partial T_2/\partial c_{R2} > 0$, we conduct comparative dynamic analysis of (15) and (19)–(22), which form a system of equations with variables $\{\mu, T_1, T_2, T_3, q_F(T_2)\}$. Applying the implicit function theorem to this system of five equations, it can be shown after some straightforward but tedious algebra that

$$\frac{\partial T_2}{\partial c_{R2}} = \frac{\left\{\left[1 - e^{r(T_1 - T_2)}\right]\left[h^{-1}(c_B) - \overline{q}_R - r\mu\Psi_1\right] + r\Psi_2(T_2 - T_1)\right\} - \frac{r\mu\left(e^{rT_2} - e^{rT_1}\right)}{\partial MR(T_2)/\partial q_F(T_2)}}{-rh'\left(h^{-1}(c_{R2})\right) \times \Psi_2\left[h^{-1}(c_B) - \overline{q}_R + \Psi_2 - r\mu\Psi_1\right]},$$

where

$$\Psi_1 = \int_0^{T_1} \frac{e^{rt}}{\partial MR(t)/\partial q_F(t)} dt + \int_{T_2}^{T_3} \frac{e^{rt}}{\partial MR(t)/\partial q_F(t)} dt < 0$$

$$\Psi_2 = h^{-1}(c_{R2}) - \overline{q}_{R1} - q_F(T_2) > 0.$$

Given the sign of Ψ_1 and Ψ_2, it can be easily checked that $\partial T_2/\partial c_{R2} > 0$.

Substep 3.3: Part (3) of the Proposition. Again, adopting the same approach as in Substep 3.1 and using (18) and (20), we know

$$\frac{\partial T_1}{\partial \overline{q}_{R2}} = \frac{\partial T}{\partial \overline{q}_{R2}} = -\frac{1}{r\mu}\frac{\partial \mu}{\partial \overline{q}_{R2}} < 0.$$

We cannot analytically derive the sign of $\partial T_2/\partial \overline{q}_{R2}$ and $\partial T_3/\partial \overline{q}_{R2}$. Next we use numerical simulations to show that a particularly interesting pattern arises where T_2 always increases in $\overline{q}_{R2}$ and T_3 first decreases and then increases in $\overline{q}_{R2}$. Suppose the energy inverse demand function is linear and is given by $p_t = \overline{p} - \beta Q_t$, and parameter values of c_F, c_{R2}, c_B, and $\overline{p}$ at \$20, \$250, \$380 and \$450 respectively. We set the initial fossil fuel reserve X_0 at the world proved oil reserve of 2013, which is around 1670 billion barrels (BP, 2013). We set the R1 capacity $\overline{q}_{R1}$ at the level of current world biofuel production, which is around 0.5 billion barrels. As standard in the literature, we set the interest rate at $r = 0.05$. Finally we let $\beta = 6$ so that current fossil fuel production $q_F(0)$ in a benchmark case of our model with $\overline{q}_{R2} = \overline{q}_{R1}$ matches the 2013 worldwide oil consumption of about 31 billion barrels per year (BP, 2013). The simulation example shows that T_2 always increases in $\overline{q}_{R2}$ and T_3 firstly decreases and then increases in $\overline{q}_{R2}$.

(II) Proof of Part (4) of the Proposition. We again take several steps, proving the effects on each individual variable.

Step 1: we prove $\partial\mu/\partial\overline{q}_{R1} < 0$ by contradiction.

Step 1.1: we show that $\partial\mu/\partial\overline{q}_{R1} \geq 0$ requires $\partial\left[(T_2 - T_1)\left(h^{-1}(c_{R2}) - \overline{q}_{R1}\right)\right]/\partial\overline{q}_{R1} > 0$. The latter inequality says that, as capacity $\overline{q}_{R1}$ rises, the fossil fuel extraction during period $[T_1, T_2]$ increases. Suppose $\partial\mu/\partial\overline{q}_{R1} \geq 0$ is true. Then applying the implicit function theorem to (14) and using the assumption that the demand function $h(\cdot)$ is linear, we know $\partial q_F(t)/\partial\overline{q}_{R1} = (1/2h')(e^{rt}\partial\mu/\partial\overline{q}_{R1} - h') < 0$, for all $t \in [0, T_1)$. Similarly, from (16), we know $\partial q_F(t)/\partial\overline{q}_{R1} < 0$ for all $t \in [T_2, T_3)$. For $t \in [T_1, T_2)$, the fossil fuels are supplied to stave off R2, and as shown earlier, $q_F(t) = h^{-1}(C_{R2}) - \overline{q}_{R1}$, again implying that $\partial q_F(t)/\partial\overline{q}_{R1} < 0$. Similarly, from (17), we have $\partial q_F(t)/\partial\overline{q}_{R1} < 0$ for all $t \in [T_3, T)$. Thus, $\partial q_F(t)/\partial\overline{q}_{R1} < 0$ during each of the four stages. Moreover, from (18), $\partial\mu/\partial\overline{q}_{R1} \geq 0$ also implies that $\partial T/\partial\overline{q}_{R1} < 0$. Therefore, if $\partial\mu/\partial\overline{q}_{R1} \geq 0$, then as $\overline{q}_{R1}$ increases, the fossil fuels are not only extracted less in each period of each stage but also depleted in a shorter period of time. As illustrated in Fig. 9(b), when each segment of the supply function $q_F(t)$ decreases, the only time periods when resource extraction can be higher than before is during $[T_2, T'_2]$ and during $[T, T']$. However, since we just established that, under the assumption of $\partial\mu/\partial\overline{q}_{R1} \geq 0$, the exhaustion time T decreases, i.e., $T' < T$, the only time period during which resource extraction can be higher is during $[T_2, T'_2]$. Thus, to satisfy the resource exhaustion condition, total extraction during this period must be higher to compensate for the decreased resource extraction during all other periods and the earlier exhaustion time. Recall that the monopolist staves off R2 during this period by supplying a constant amount, $q_F(t) = h^{-1}(c_{R2}) - \overline{q}_{R1}$ for $t \in [T_1, T_2)$, The total extraction thus equals $(T_2 - T_1)(h^{-1}(c_{R2}) - \overline{q}_{R1})$, establishing that $\partial[(T_2 - T_1)(h^{-1}(c_{R2}) - \overline{q}_{R1})]/\partial\overline{q}_{R1} > 0$.

Step 1.2: we next show that $\partial\left[(T_2 - T_1)\left(h^{-1}(c_{R2}) - \overline{q}_{R1}\right)\right]/\partial\overline{q}_{R1} > 0$ cannot be true. We use comparative statics to drive the effect of $\overline{q}_{R1}$ on $(T_2 - T_1)\left(h^{-1}(c_{R2}) - \overline{q}_{R1}\right)$, using equations (15), (20) and (21). We can take μ as a function of $\overline{q}_{R1}$ and solve for $\{T_1, T_2, q_F(T_2)\}$. Applying the implicit function theorem,[10] we obtain

$$\frac{\partial\left[(T_2 - T_1)\left(h^{-1}(c_{R2}) - \overline{q}_{R1}\right)\right]}{\partial\overline{q}_{R1}} = \frac{h\left(q_F(T_2) + \overline{q}_R\right) - c_{R2} + h'\left(h^{-1}(c_{R2})\right)e^{r(T_2 - T_1)}\Lambda - (T_2 - T_1)\,r\mu e^{rT_2}\Lambda}{r\mu e^{rT_2}\Lambda}, \tag{40}$$

[10] The comparative statics leads to

$$\begin{pmatrix} -r\mu e^{rT_1} & 0 & 0 \\ 0 & -r\mu e^{rT_2} & \frac{\partial MR(T_2)}{\partial q_F(T_2)} \\ 0 & r\mu e^{rT_2}\Lambda & 0 \end{pmatrix} \begin{pmatrix} \frac{\partial T_1}{\partial \overline{q}_{R1}} \\ \frac{\partial T_2}{\partial \overline{q}_{R1}} \\ \frac{\partial q_F(T_2)}{\partial \overline{q}_{R1}} \end{pmatrix} = \begin{pmatrix} h'\left(h^{-1}(c_{R2})\right) + e^{rT_1}\partial\mu/\partial\overline{q}_{R1} \\ -h'\left(q_F(T_2) + \overline{q}_R\right) + e^{rT_2}\partial\mu/\partial\overline{q}_{R1} \\ h\left(q_F(T_2) + \overline{q}_R\right) - c_{R2} - e^{rT_2}\Lambda\partial\mu/\partial\overline{q}_{R1} \end{pmatrix}.$$

where $\Lambda = h^{-1}\left(c_{R2}\right) - \overline{q}_R - q_F\left(T_2\right) > 0$. It is clear from (40) that the sign of the right hand side is determined by the numerator, which is monotonically decreasing in $T_2 - T_1$. If the demand function is linear and $T_2 - T_1 = 0$, then after substituting in Λ, this numerator becomes

$$h\left(q_F\left(T_2\right) + \overline{q}_R\right) - c_{R2} + h'(\cdot)\left[h^{-1}\left(c_{R2}\right) - \overline{q}_R - q_F\left(T_2\right)\right].$$

This expression equals zero because under linear demand,$h(q_F(T_2) + \overline{q}_R) = a - b \cdot [q_F(T_2) + \overline{q}_R]$, and $c_{R2} = a - b \cdot h^{-1}\left(c_{R2}\right)$, where a and $b \equiv -h'(\cdot)$ are respectively the intercept and slope of the linear demand function. That is, when $T_2 - T_1 = 0$, we have $\partial[(T_2 - T_1)(h^{-1}(c_{R2}) - \overline{q}_{R1})]/\partial\overline{q}_{R1} = 0$. Since $T_2 - T_1 > 0$ always holds, we must have $\partial[(T_2 - T_1)(h^{-1}(c_{R2}) - \overline{q}_{R1})]/\partial\overline{q}_{R1} < 0$, which contradicts the condition derived in step 1.1. Hence $\partial\mu/\partial\overline{q}_{R1} \geq 0$ cannot be true, completing the Proof for $\partial\mu/\partial\overline{q}_{R1} < 0$.

Step 2: results related to the impacts on switch times. With $\partial\mu/\partial\overline{q}_{R1} < 0$, the signs of $\partial T_1/\partial\overline{q}_{R1}$, $\partial T_3/\partial\overline{q}_{R1}$ and $\partial T/\partial\overline{q}_{R1}$ can be derived from differentiating (20), (22) and (18) with respect to $\overline{q}_{R1}$:

$$\frac{\partial T_1}{\partial\overline{q}_{R1}} = -\frac{h'(\cdot) + e^{rT_1}\partial\mu/\partial\overline{q}_{R1}}{r\mu e^{rT_1}} > 0,$$

$$\frac{\partial T_3}{\partial\overline{q}_{R1}} = -\frac{h'(\cdot) + e^{rT_3}\partial\mu/\partial\overline{q}_{R1}}{r\mu e^{rT_3}} > 0,$$

$$\frac{\partial T}{\partial\overline{q}_{R1}} = -\frac{e^{rT}\partial\mu/\partial\overline{q}_{R1}}{r\mu e^{rT}} > 0.$$

The comparative statics exercise in footnote 10 yields

$$\frac{\partial T_2}{\partial\overline{q}_{R1}} = \frac{h\left(q_F\left(T_2\right) + \overline{q}_R\right) - c_{R2} - e^{rT_2}\Lambda\partial\mu/\partial\overline{q}_{R1}}{r\mu e^{rT_2}\Lambda} > 0.$$

The inequality follows from the facts that $\Lambda > 0$, $h\left(q_F\left(T_2\right) + \overline{q}_R\right) > c_{R2}$, and $\partial\mu/\partial\overline{q}_{R1} < 0$.

Step 3: results related to the impacts on qF(t), t < T1. Given the linear demand function, we can differentiate (14) with respect to $\overline{q}_{R1}$ and show that, for any $t \in [0, T_1]$,

$$\frac{\partial q_F(t)}{\partial\overline{q}_{R1}} = -\frac{h'(\cdot) - e^{rt}\partial\mu/\partial\overline{q}_{R1}}{2h'(\cdot)}.$$

Evidently $\partial q_F(t)/\partial\overline{q}_{R1}$ monotonically increases over time during $[0, T_1]$, as $\partial^2 q_F(t)/\partial\overline{q}_{R1}\partial t = re^{rt}\left(\partial\mu/\partial\overline{q}_{R1}\right)/\left[2h'(\cdot)\right] > 0$. Moreover, since $q_F\left(T_1\right) = h^{-1}\left(c_{R2}\right) - \overline{q}_{R1}$, we have $\partial q_F\left(T_1\right)/\partial\overline{q}_{R1} < 0$. The two conditions ensure that $\partial q_F(t)/\partial\overline{q}_{R1} < 0$ for any $t \in [0, T_1]$. ∎

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